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Laser brazing with beam scanning: Experimental and simulative analysis

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Abstract

Laser beam brazing with copper based filler wire is a widely established technology for joining zinc-coated steel plates in the body-shop. Successful applications are the divided tailgate or the zero-gap joint, which represents the joint between the side panel and the roof-top of the body-in-white. These joints are in direct view to the customer, and therefore have to fulfil highest optical quality requirements. For this reason a stable and efficient laser brazing process is essential.
In this paper the current results on quality improvement due to one dimensional laser beam deflections in feed direction are presented. Additionally to the experimental results a transient three-dimensional simulation model for the laser beam brazing process is taken into account. With this model the influence of scanning parameters on filler wire temperature and melt pool characteristics is analyzed.
The theoretical predictions are in good accordance with the experimental results. They show that the beam scanning approach is a very promising method to increase process stability and seam quality.

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Keywords: laser brazing; zinc-coated steel plate; zero-gap joint; joint quality; laser brazing simulation

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1. Motivation

Laser beam brazing of galvanized steel sheets with a copper based filler wire is an effective process for reaching excellent joint quality and high joint strength. Therefore it is widely applied in the automotive industry, especially on exposed parts like roofs and divided tailgates, which is described in Graudenz and Heitmanek (2012). The principle of laser beam brazing is to fill a gap between two steel sheets by melting a filler wire that wets the surfaces and joins them after solidification. The energy for the fusion of the filler wire is applied by a laser beam (Fig.1).

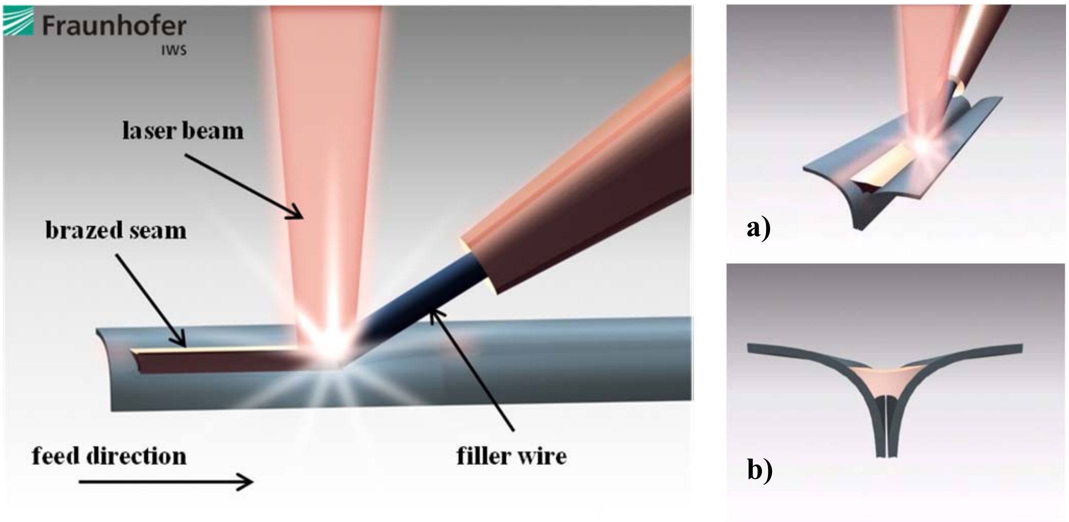


Fig. 1. Principle of laser beam brazing. (a) isometric and (b) cross section.

The main parameters for brazing with a static laser beam are the brazing speed, the filler wire speed and the laser power. Sometimes a electrical resistive pre-heating of the filler wire is used as a additionally energy input to get a better surface quality, see Mathieu et al. (2006). Furthermore the joining of the roof with the side panels, so called zero-gap joint, is a process on the end of the body shop and therefore it has to overcome all the accumulated former process variations, e.g. different steel surface qualities and gap situations. Additionally there are many influencing variables which change during the process as shown in Heitmanek and Graudenz (2012). Under this circumstances the laser brazing process with a fixed optic reaches its limitations, especially at higher brazing speed (3 m/min). The wetting frequency of the melt pool front is correlated to the brazing speed. As a result surface quality is influenced by this frequency, as described in Grimm (2012). Experiments showed that laser beam shaping and thus the energy input influences the brazing process especially related to the wetting behaviour and the fusion zone, see LI et al. (2008). Other possibilities for beam shaping are coaxial or twin spot optics, as described in Grimm et al. (2010).

This study examines the modulation of the energy input due to laser beam oscillation in feed direction. With the flexibility in the dynamic beam shaping the effects of scan frequency and focus elongation on the joint quality are investigated. Additionally it is possible to modulate the energy input over the scanning elongation, e.g. to get more energy on the front of the process zone for a better fusion of the filler wire. However the main question is, if one dimensional laser beam scanning can lead to better quality results of the joint, e.g. by influencing the wetting frequency.

2. Experimental set-up

For the experiments galvanized steel sheets were brazed with a copper based filler wire on a transversal flange joint configuration. As energy source a high-power diode laser and for the manipulation of the laser beam a optic "LASSY" from Fraunhofer IWS were used. With this optic it is possible to generate a maximum scan frequency of the mirror of 200 Hz, see Bonss et al. 2007. The set-up configuration and the main parameters for the experiments are summarized in table 1. Furthermore the set-up is shown in Fig. 2.

Table 1. Experimental set-up and main parameters.

Experimental set-up	
Laser source	Diode laser, LDF 400-5000
Optic with scan mirror	LASSY (IWS)
Max. frequency of scan mirror	200 Hz
Collimation	70 mm
Focal length	600 mm
Fiber diameter	400 µm
Steel sheets	DC06 + ZE75/75 (t=0,75 mm)
Filler wire	CuSi3 (Ø 1,6 mm)
HS-Camera	Photon focus (850 fps)
Pyrometer	IWS (8,7 kHz)
Parameters	
Laser power (P_L)	3-3,8 kW
Brazing velocity (v_R)	3,0 m/min
Filler wire speed (v_W)	3,2 m/min
Wire preheating	None

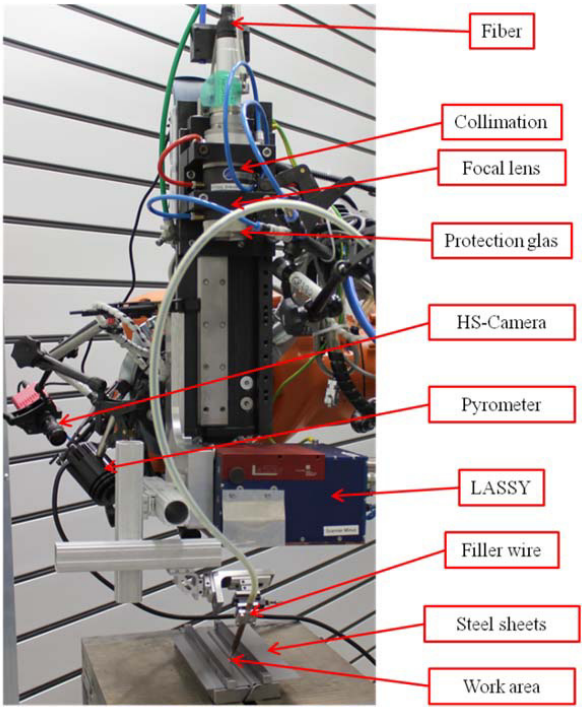


Fig. 2. Experimental set-up.

The one dimensional scanning was used in feed direction to obtain the influence of the beam shaping on the wetting behavior and on the melt pool. For example if the vaporization of the zinc layer is getting separated from the melt pool front. Or if it's possible to get a smoother surface quality by having a longer melt pool. The principle of scanning in feed direction is shown by a visible pilot laser in Fig. 3.

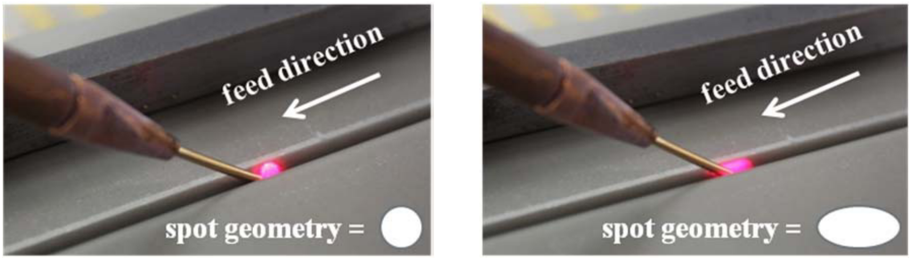


Fig. 3. Principles for spot geometries in the work area.

Additionally a optical pyrometer with a frame rate of 8,7 kHz was installed in the experimental set-up, to characterize the oscillation of the melt pool front more detailed. The pyrometer spot was fixed to the area, where the filler wire is melting and the wetting to the steel plates is happening, as shown in Fig.4.

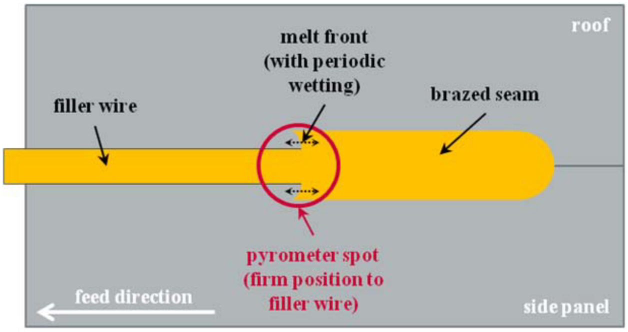


Fig. 4. Position of the pyrometer spot.

For the evaluation of the joint quality on the one hand the surface quality is obtained and on the other hand the connection width (s_{NL}) of the joint is investigated. Fig. 5 shows the measurement of s_{NL}. The minimal connection width defines the maximum load, which can be applied to the joint.

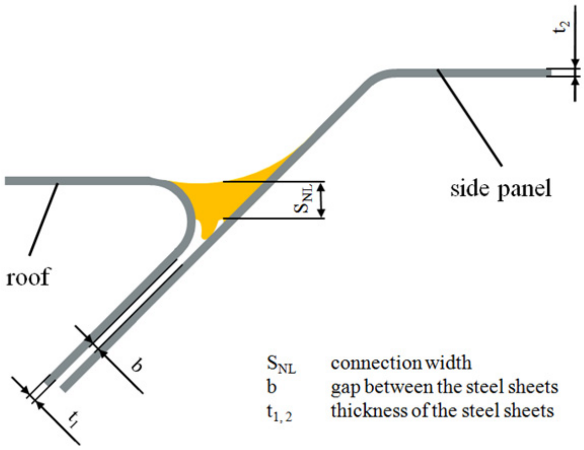
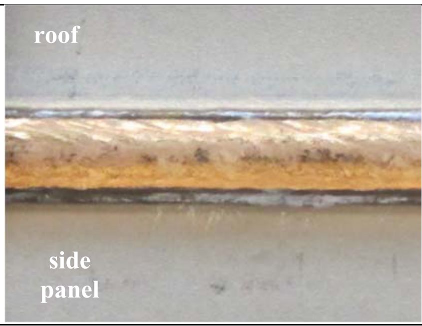
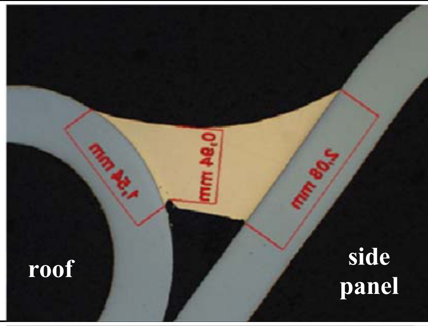
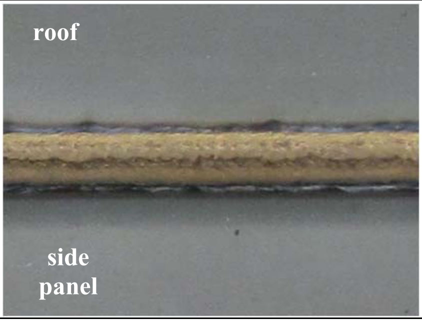
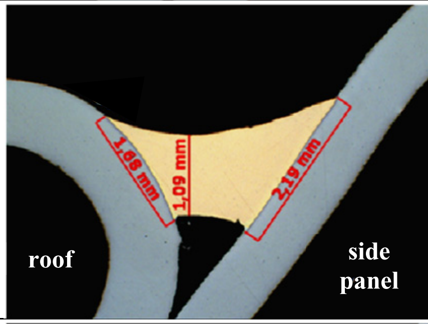
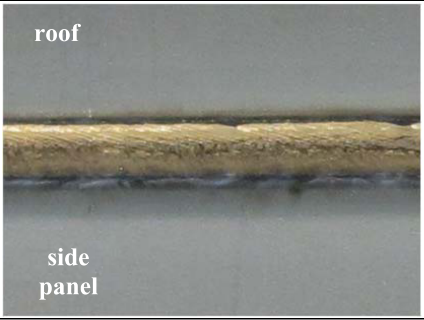
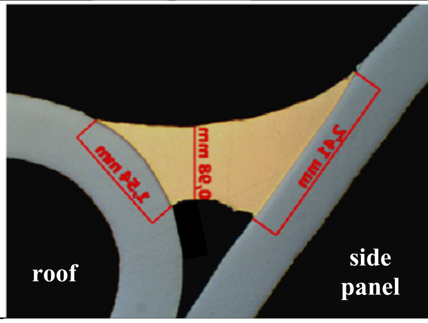


Fig. 5. Connection width (s_{NL}) in the cross section.

3. Experimental results

The results of surface quality and connection width in the cross section due to laser beam deflections shows table 2. The laser power, the brazing speed and the filler wire speed were constant during the laser beam brazing. For small deflections (4.4 mm) of the laser beam there is a higher joint quality. That means, the surface is more homogenous and the connection width increases. With greater deflection the laser power has to be increased to reach higher connection widths. In this case the surface of the brazed seam is getting rougher and the quality drops down. Additionally a melting of the steel sheets can happen, which decreases the corrosion resistance. For beam deflections greater than 5.5 mm it was not possible to reach a reproducible process. For this elongations a lot of imperfections on the surface (pores, holes, one sided wetting) occurred.

Table 2. Results for laser beam brazing with different deflections in feed direction (P_L=3,6 kW; v_R= 3 m/min, v_W= 3,2 m/min).

Parameters	Surface	Cross section
Beam deflection 0 mm (static)		
Beam deflection 4,4 mm (dynamic)		
Beam deflection 5,5 mm (dynamic)		

The frequency of the scan mirror and thus the energy input in feed direction was varied for the brazing speed of 3 m/min. The Fig. 6 presents the results of the measured connection width over the frequency of the scan mirror. The minimum of requirement is 0.8 mm, because of the finish processes that are following afterwards in the production line. For the non scanning process (0 Hz, static) the connection width can be lower. In this case the maximum reachable width is around 1 mm. An increase of the frequency leads to a higher connection width when laser power, brazing speed and filler wire speed are kept constant. Especially for frequencies over 100 Hz the process is very stable and homogenous. This is related to the better preheating of the steel sheets, the improved wetting behavior from lower amount of molten material for one wetting cycle and the resulting lower position in the transversal flange joint.

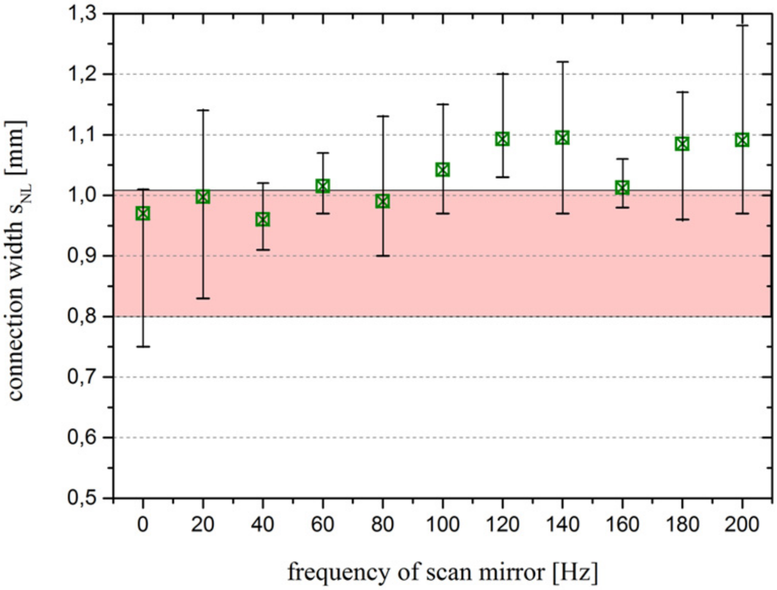


Fig. 6. Increase of the connection width over the frequency of the scan mirror.

The improved wetting behavior on higher frequencies was also observed in high speed videos. On a frame rate of 850 fps the dynamic of the molten filler wire was lower compared to the static process. With higher frequencies the amount of the molten filler wire material for each wetting cycle decreases. With the installed pyrometer the oscillation of the melt pool front was investigated. Fig. 7 present the variation of the temperature signal of the melt pool front for a non scanned process (0 Hz, static) over 100 ms.

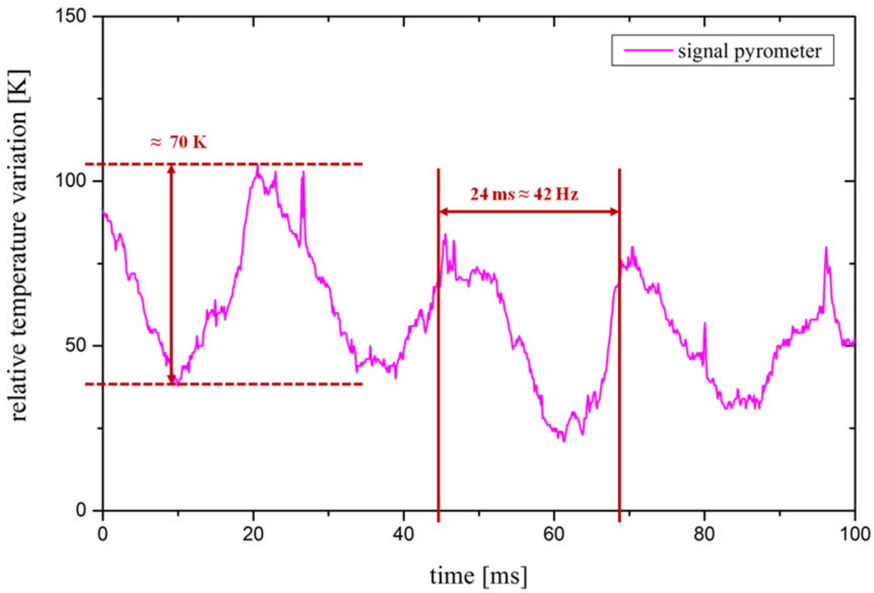


Fig. 7. Pyrometer signal for static process (scanning frequency = 0 Hz).

The temperature variation in the static process is around 70 K. Furthermore the graph shows a characteristic frequency of the wetting behavior related to the pulsating melt pool. The resonant frequency is around 40 Hz for a brazing speed of 3 m/min. This resonant frequency of the melt pool front is getting higher with increasing brazing speed, which is also described in Grimm (2012). The periodic fusion of the filler wire leads to a periodic wetting behavior.

For a frequency of the scan mirror of 200 Hz the pyrometer signal is shown in Fig. 8. The resonance frequency of the temperature signal is around 200 Hz, which shows the correlation to the oscillation frequency of the laser beam. The temperature variation decreases (30-50 K) compared to the non scanned process. The amount of the molten wire material, which has to wet the steel sheets, decreases. As a result of the higher beam scan frequency the surface of the brazed seam is smoother. The reason for that is the better wetting behavior, which shows that beam scanning influence the joint quality positively.

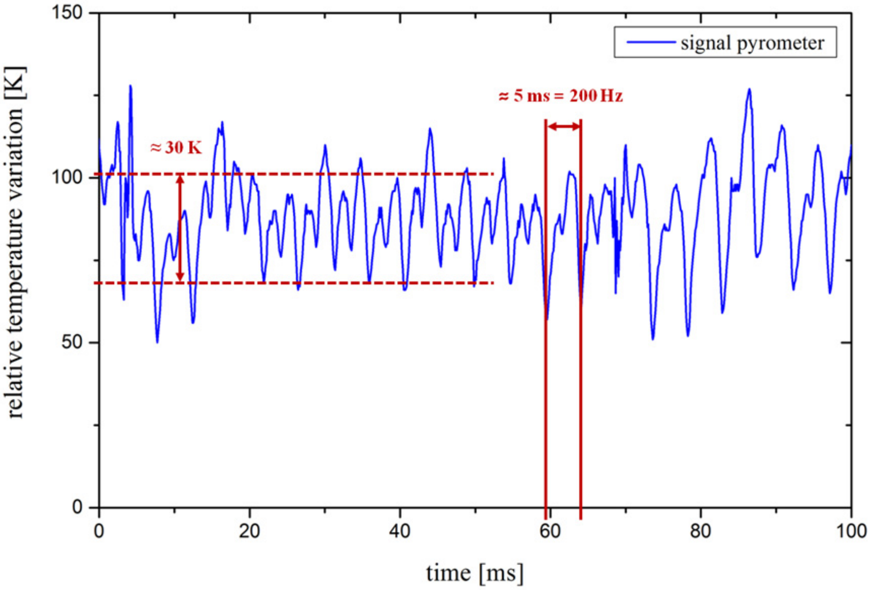


Fig. 8. Pyrometer signal for dynamic process (scanning frequency = 200 Hz).

4. Simulation model

To obtain more detailed information about laser beam brazing with beam deflection, the process was also investigated with a transient three-dimensional simulation model. This model can provide temporally and spatially resolved information about the process which is experimentally not available. For example, exact experimental measurements of the CuSi melt pool and wire temperature are not easily possible. Thermographic measurement can provide information about the temperature field, but absolute temperatures are difficult to obtain. A multi-physical model in which beam propagation, heat transfer and melt dynamics are implemented can reveal temperature distributions as well as melt pool characteristics of the brazing process with beam scanning.

The used multi-physical simulation model has already been applied to various processes in laser material processing. For example laser beam welding, melting and cutting (i.e. Kohl et al. 2012) were analyzed. The model is based on the finite volume method and is implemented by means of the computational fluid dynamics code OpenFOAM.

Laser beam propagation, heat transfer as well as melt and wetting dynamics are included in the model. Details of the implementation are discussed in Dobler et al. (2013). Validation results for the seam cross section of this simulation model for laser brazing are also presented in Dobler et al. (2013). The cross sections obtained with the simulation model are in good agreement with experimental results.

In the simulations the same process parameters as in the experiments are used (see table 1).

5. Simulation results

5.1. Temporal oscillation of the filler wire temperature

Oscillation of the laser beam strongly influences the spatial distribution of the energy input. This leads to significant changes of the temperature fields compared to the standard process without beam oscillations. The simulation model enables a temporal and spatial resolution of these temperature distributions. In Fig. 9 the calculated temperature oscillations on the filler wire surface (position: 1.5 mm in feed direction from the TCP) are depicted.

a) b)

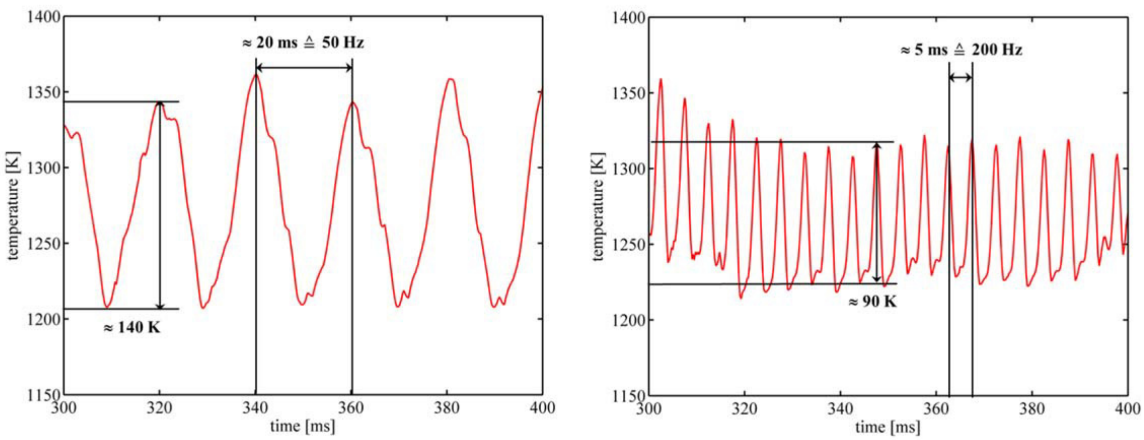


Fig. 9. Temperature on the filler wire for different oscillation frequencies (a) 50 Hz; (b) 200 Hz at a deflection of 4.5 mm.

The simulations show that the beam scanning leads to the expected oscillations of the filler wire temperature, which are in accordance with the pyrometer measurements shown in Fig. 8. The frequency of the temperature oscillation matches the frequency of the beam scanning.

The difference of minimum and maximum temperature is about 140 K for f = 50 Hz and 90 K for f = 200 Hz. As the higher oscillation frequency reduces cooling times between two consecutive heating cycles by the laser beam, the temperature differences are decreased for fast oscillations.

5.2. Melt pool characteristics

As the experimental results showed, beam scanning changes the process dynamics and the characteristics of the obtained seam cross section. However, an analysis of the melt pool characteristics is difficult to perform with experimental methods. Therefore the simulation model is used to analyze how the change in energy input by means of beam scanning effects the melt pool characteristics. Fig. 10 shows longitudinal sections of the filler material for varying maximum deflections of the laser beam. In each depicted case the laser beam is at zero position (inclination angle 0°).

An increased deflection leads to a longer melt pool, as a larger area of the melt pool surface is heated. However, the temperature in the melt pool declines with increased scanning deflections. The average melt pool temperature decreases with the deflection. While the average melt pool temperature calculated with the simulation model in the static case is about 1660 K, the temperature decreases to 1600 K at a deflection of 5.4 mm and 1510 K at a deflection of 7.2 mm.

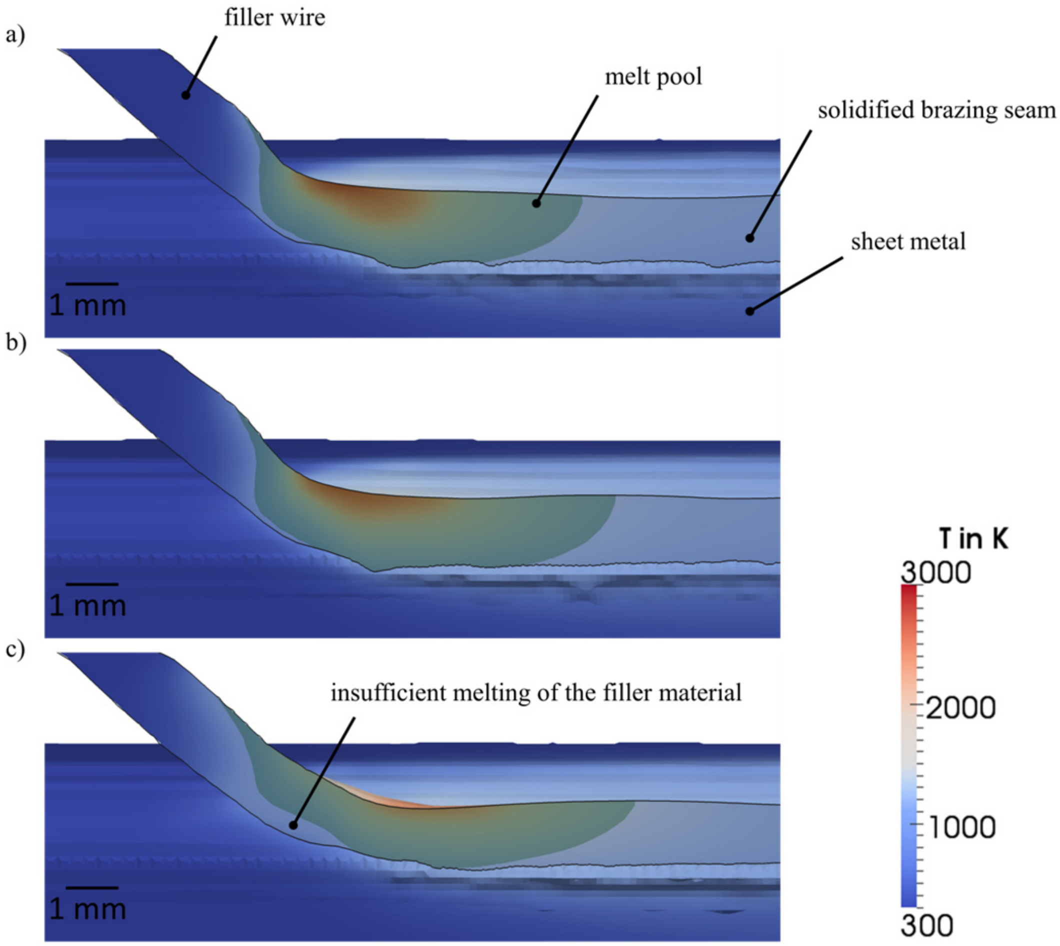


Fig. 10. Longitudinal section of the filler material, fully molten material colored in green. (a) no deflection; (b) 5.4 mm deflection; (c) 7.2 mm deflection. In cases b) and c) a scanning frequency of 200 Hz is used.

Another major difference in melt pool formation can be seen when comparing scanning deflections of 5.4 mm and 7.2 mm. A smaller deflection leads to a more complete melting of the filler wire. In the latter case, the lower parts of the wire below the melt pool surface remain solid. The large amount of unmolten CuSi material is assumed to contribute to the unsatisfying experimental results for brazing with beam deflections of 7.2 mm. The unmolten filler wire and the lower melt temperature at high deflections are assumed to inhibit the wetting of the sheet metal and consequently lead to reduced connection width and an increased occurrence of brazing errors. This result suggests that conductive preheating of the filler wire may be used to increase the filler wire temperature, so that high quality brazing with large beam deflections becomes feasible.

6. Conclusion

The experiments show the positive effects of using beam scanning in feed direction for laser brazing of galvanized steel sheets. Furthermore, the wetting frequency of the melt pool follows the energy input by frequency of the scan mirror. With beam scanning it is possible to influence the amount of the molten material and thereby the wetting behavior. With constant brazing parameters (brazing velocity, filler wire speed, laser power) the connection width increases in comparison to the static process related to the better preheating. The calculations show that temperatures on the filler wire are strongly affected by beam oscillations. An analysis of the melt pool characteristics shows a significant effect of oscillation amplitude on melt pool size and filler wire melting. Improvements of the simulation model like implementation of the zinc layer on the metal sheets and application of temperature dependent material properties will enhance the quantitative accuracy of the model in the future.

The theoretical predictions are in good accordance with the experimental results, they show that the beam scanning approach is a very promising method to increase process stability and surface quality in laser beam brazing. The results of both experiments and simulations show that beam scanning can be applied to effectively influence the laser beam brazing process so that process stability and surface quality are improved.

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